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Thermoacoustic Natural Gas Liquefier

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Introduction

Cryenco and Los Alamos are collaborating to develop a natural-gas-powered natural-gas liquefier that will have no moving parts and require no electrical power. It will have useful efficiency, remarkable reliability, and low cost.

The liquefaction of natural gas, which occurs at only 115 Kelvin (-250°F) at atmospheric pressure, has previously required rather sophisticated refrigeration machinery. The 1990 invention of the thermoacoustically driven orifice pulse-tube refrigerator (TA-DOPTR) provides cryogenic refrigeration with no moving parts for the first time. In short, this invention uses acoustic phenomena to produce refrigeration from heat. The required apparatus consists of nothing more than helium-filled heat exchangers and pipes, made of common materials, without exacting tolerances. In the Cryenco-Los Alamos collaboration (with the Los Alamos tasks supported by the US Department of Energy), we are developing a version of this invention suitable for use in the natural-gas industry. The project is known as "acoustic liquefier" for short.

Our present program plans call for a two-phase development. Phase I, with capacity of 500 gallon per day (i.e., approximately 40,000 scfd, requiring a refrigeration power of about 7 kW), is large enough to illuminate all the issues of large-scale acoustic liquefaction without undue cost, and to demonstrate the liquefaction of 60-70% of input gas, while burning 30-40%. Phase II will target versions of approximately 10^6 scfd = 10,000 gallon per day capacity. In parallel with both, we continue fundamental research on the technology, directed toward increased efficiency, to build scientific foundations and a patent portfolio for future acoustic liquefiers.

Objectives

Although most natural gas is still carried from well to user as gas in pipelines, the use of liquefied natural gas (LNG) [1] has been increasing 5-10% per year. Large liquefaction plants and cryogenic storage tanks exist throughout the US, close to major consumption centers for seasonal peakshaving. In this practice, relatively constant flow of gas through pipelines from the gas fields to load centers can be maintained throughout the year by liquefying and storing the excess when demand is low in summer and vaporizing it as needed when demand increases in winter. Fleet-vehicle use of LNG as fuel is increasing

[1] Research sponsored by the U. S. Department of Energy's Federal Energy Technology Center, under Work Authorization Number AB/05 686/AL/03 to the Los Alamos National Laboratory, which is operated by the University of California.

rapidly. Worldwide, LNG ocean transport vessels of 10^5 m^3 capacity are also commonplace, as are attendant coastal LNG facilities.

With a liquefaction temperature of only 115 Kelvin (-250°F), natural gas has (until now) required rather sophisticated refrigeration machinery. A typical modern, large liquefaction plant costs a billion dollars, liquefies 10^9 scfd, uses 15% of its throughput to power itself, and has substantial operating and maintenance costs. The need for smaller, reliable, inexpensive liquefaction equipment is clear.

Approach

Scientists at Los Alamos National Laboratory and the National Institute of Standards and Technology (NIST) invented [2] the TADOPTR, [3] and built a small experimental version [4] directed toward cooling of infrared sensors on satellites. Development of a more compact version [5] was later undertaken in a Tektronix-Los Alamos-NIST collaboration. This invention and development follows a long evolution of related devices, each directed toward elimination of moving parts from heat engines and refrigerators.

Stirling-cycle [6] refrigeration, over a century old, has historically required two moving pistons, one of which is in contact with the cold temperature. In 1963, Gifford and Longsworth discovered a refrigeration technique which eliminated the cold piston. They called this new technique pulse-tube refrigeration. In 1984, Mikulin made a significant fundamental advance, adding a flow resistance; such “orifice” pulse-tube refrigerators, [7] developed largely at NIST-Boulder, now routinely reach 50 Kelvin in a single stage. The addition of a bypass valve to the pulse-tube refrigerator, discovered by Zhu, Wu, and Chen [8] in 1990, promised to bring the efficiency of pulse-tube refrigerators near that of Stirling refrigerators. The pulse-tube refrigerator’s importance is primarily due to the elimination of the cold piston, a significant simplification leading to high reliability.

Until recently, pulse-tube refrigerators still required one moving piston, at ambient temperature. Los Alamos and NIST eliminated this last moving part, substituting for it a thermoacoustic engine. Thermoacoustic engines [9, 10] generate an acoustic standing wave from heat, thus producing oscillating pressure at the frequency of the standing-wave resonance. Although thermoacoustic devices were discovered and explained qualitatively a century ago, research at Los Alamos (sponsored by the US Department of Energy’s Office of Basic Energy Sciences) has led to quantitative understanding and the first attempts at practical implementations.

Project Description

From the beginning of the Cryenco-Los Alamos collaboration, the development of a practical acoustic liquefier appeared very challenging. Even the 500 gallon per day prototype represents a scaleup of a factor of 1600 in cooling power over the best previous TADOPTR, [4] which used much simpler electric heater power for the engine and an electric-heat test load on the refrigerator, and had an efficiency implying that it would have liquefied only 9% of a natural-gas stream while burning the other 91%. To address this great challenge, our project encompasses three parallel thrusts:

1. Prototype development. As described in the introduction, we chose to break the development into two phases, with target capacities of 500 gallons per day in Phase I and 10,000 gallons per day in Phase II.

2. Interaction and cooperation. To develop the Phase-I prototype as quickly as possible, while using the strengths of each partner and allowing thermoacoustics skills to grow among Cryenco personnel, we have adopted a highly interactive working relationship. Los Alamos personnel have been at Cryenco one-third of the time, and daily telephone contact is the norm at other times. Most physics design and test-and-measurement duties have been Los Alamos responsibilities, while most engineering and almost all hardware and test-facility construction have been Cryenco responsibilities. Lunchtime lectures and discussions at Cryenco help personnel there learn the fundamentals of thermoacoustics, and test reports and software written at Los Alamos are used to document important design procedures for future reference at Cryenco.

3. Science and fundamental invention. Because TADOPTR technology is so new, opportunities still exist for dramatic improvements based on fundamental understanding. Hence, Los Alamos continues fundamental applied research on TADs and OPTRs, with a focus on patentable inventions leading to improved efficiency without sacrificing high reliability or low cost.

Accomplishments

The 500 gallon per day prototype will comprise two identical thermoacoustic engines and three identical orifice pulse tube refrigerators sharing a common resonator. In the past year, we designed, built, and assembled the first pieces of this prototype: one engine and one refrigerator on the resonator. Testing of this assembly with a burner heating the engine began in January 1997, and as of March the assembly produced LNG at a rate of 100 gallons per day. Testing is ongoing, but it appears certain that capacity design goals will be met, and probable that efficiency goals will be met.

This important milestone demonstrates for the first time that TADOPTR technology works at a capacity suitable for practical liquefaction of natural gas.

Construction and assembly of the engine, refrigerator, and resonator were difficult, and many engineering challenges were discovered and overcome in all three components. Each problem was fixed as quickly as possible, but each fix was also regarded as an opportunity to reduce the projected cost to manufacture the acoustic liquefier. The resulting dramatic reduction in projected costs achieved this year was unexpected, and is a milestone as important as the 100-gallon-per-day capacity demonstration.

Fundamental work at Los Alamos this year broke new ground in several areas. A new type of thermoacoustic heat exchanger with tube-in-shell geometry was tested successfully. Turbulent limitations to the use of variable acoustic impedance in OPTRs were explored, and a control method was invented (provisional patent filed; final patent in preparation). Both these developments were completed in time to be used in the Cryenco prototype, where they are working as well as predicted. A third invention, use of a tapered pulse tube to suppress streaming-driven convection (patent to be filed), was also demonstrated at small scale at Los Alamos and incorporated into the Cryenco prototype; testing of this feature at Cryenco is not yet complete.

Applications

The efficiency of small acoustic liquefiers will be reasonable, although not as high as that of conventional large-scale liquefiers, which have enjoyed decades of engineering development. We expect the first 500 gallon per day production units to liquefy 70% of throughput, and the first 10,000 gallon per day production units to liquefy 75-80% of throughput. Later research should lead to improved efficiency.

The acoustic liquefier will offer unsurpassed reliability. Because it has no exotic materials or close tolerances anywhere (it is nothing more than welded piping and heat exchangers), its cost will be very low, and it will be economical at a size far smaller than that of existing LNG equipment. These features are suited to a wide range of applications, at small, medium, and large capacity:

Small capacity (approximately 500 gallons per day): Local liquefaction of pipeline gas at fleet-vehicle fueling stations; recovery of landfill gas and other bio-waste gas; recovery of associated gas from small oil wells; recovery of coal bed (gob) gas; boiloff recovery at seasonal peak-shaving facilities; liquefaction of gas for storage near emergency facilities such as hospitals.

Medium capacity (approximately 10,000 gallons per day): Production from shut-in wells; recovery of associated gas from offshore oil wells; liquefaction at seasonal peakshaving facilities; and most of the applications listed above for small capacity.

Large capacity (much larger than 10,000 gallons per day): It is premature to predict the acoustic liquefier's efficiency, reliability, and cost at such large scales, but it is possible that large-scale gas production in extremely hostile environments will be enabled by this technology's intrinsic high reliability.

Future Activities

We will complete testing the present one-engine-one-refrigerator subassembly of the 500 gallon per day prototype, and then complete the 500 gallon per day prototype. Improvements to vital auxiliary subsystems, such as the burner regenerators, will be necessary before production planning can begin. Near the completion of the 500 gallon per day prototype, we will begin planning the 10,000 gallon per day prototype.

We will continue research directed at improved efficiency. So far, we have identified 4 potential improvements to OPTR technology and 3 potential improvements to TAD technology. Inertance and tapered pulse tubes (discussed above) are the first two of these that we have completed. Each of these 7 improvements can potentially contribute about a 20% increase in system efficiency; hence, if all of them worked, this would represent a $(1.2)^7$ = 3-fold improvement in TADOPTR efficiency, which would imply an acoustic liquefier efficiency comparable to that of the best existing large-scale conventional LNG plants. That is probably too optimistic; but we expect that most of the 7 will indeed succeed.

Acknowledgments

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[3] A computer animation and short description of the essential thermodynamic and acoustic processes in the TADOPTR can be obtained from Greg Swift or via Internet at http://rott.esa.lanl.gov by selecting “Educational demonstrations”.

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